

OPTICAL MAGNETIC FIELD DIAGNOSTICS FOR THE MC1 FLUX COMPRESSION GENERATOR EXPERIMENTS*

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Abstract

We describe the optical diagnostics used to measure magnetic fields up to 11 MGauss (1100 T) produced by Russian MC1 magnetic flux compression generators propelled by American high explosives in a joint experiment. The fields were measured by Faraday rotation in glass samples placed between thin polarizers. Light was introduced and collected in multi-mode fiber optics, allowing the laser light source and the recording instrumentation to be housed in a bunker about 20 m from the explosion. Great care was taken to keep the volume of the diagnostics small so that they would survive the generator implosions long enough to complete the measurements.

Introduction

In Dec., 1993, a joint team from the US and Russia carried out a series of five experimental physics shots using Russian MC1 explosive-driven flux compression generators. In addition to studying the performance of the generators with two types of US explosives, this team measured the complex microwave conductivity and the upper critical field of the high-temperature superconductor, $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO), and the non-linearity in the Faraday rotation of 543 nm wavelength light in the semiconductor CdS, both as a function of the magnetic field strength. In this paper we describe the optical diagnostics that were used to measure the magnetic fields for these experiments and briefly report some of the results. A detailed description of the experiments is given elsewhere in this meeting¹, and a report on the YBCO data has also been published.²

Experimental outline

The first of the five experimental shots was designed to achieve the maximum possible magnetic field with an explosive, Composition B, that closely matched what the Russian members of the team had been using. On this shot we tried to make a careful comparison of the magnetic field diagnostics, optical and inductive, so that on subsequent experiments we could rely on one of them should there be a partial failure or, if space limitations required, should we be limited to fielding only one magnetic sensor. There were three magnetic field measurements: inductive ($B\cdot$) sensors; a lead-doped "flint" glass Faraday rotation sample, such has been fielded on many Russian experiments in the past; and Faraday rotation in a quartz sample, for direct comparison to

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past American Faraday rotation current diagnostics³, usually made directly in a low-birefringence, single-mode quartz optical fiber enclosing the current, much like a Rogowski belt.

The second shot was carried out using similar geometry but a higher-energy explosive, PBX 9501, and was intended for comparison of the performance of the two explosives. Since the field compression is obtained by squeezing a longitudinal seed field in a cylindrical geometry, it is important to keep the diagnostics confined within a small enough radius to prevent the incoming flux-compressing cascade from destroying them before it is stopped by the magnetic field pressure. For these first two experiments we fit the diagnostics into the center 12-mm diam. of a foamed plastic cylinder that initially filled the central cascade. Although the imploding cylinder and the foamed cylinder are about 20 cm long, the length of the useful high-field volume is several centimeters, and in this volume the field is thought to be uniform to about 1 %.

The three remaining shots required extensive microwave diagnostics to determine the conductivity of a superconducting sample, YBCO, being exposed to a field large enough to return it to its normally-conducting state. Since we did not need the maximum field of 900 to 1100 T to see the effect we were looking for, and since the microwave diagnostics required additional room, we expanded the diagnostic volume to be contained in an 18-mm-diam. cylinder. All of the signals were recorded on digital recorders timed to a precision of a few nanoseconds to allow synchronization of the various diagnostics.

Faraday rotation diagnostics

The principle of the Faraday diagnostic is that polarized light travelling along a magnetic field will undergo rotation of its polarization direction if the light is in a suitable medium, such as glass. The rotation angle is proportional to the line integral of the magnetic field in the medium, i.e., the longitudinal magnetic field times the path length, and the proportionality constant is the Verdet constant. In this experiment we defined the length of the Faraday rotation medium carefully, placing very thin plastic polarizers, 0.020 mm thick, on either end of the sample. The samples were made long enough to get at least a few fringes in each Faraday measurement so that there would be good precision in the rotation angle determinations.

To make the system practical to field, we used 100- μ m-diam-core fiber optics to carry the light to and from the sample, and we placed the sample midway along the axis of the magnetic field to minimize fringing effects. Graded index lenses collimated the light from the laser fibers into the samples and refocused the polarization-analyzed light back into the receiver fibers. Each assembly of fibers, lenses, polarizers, and sample was fabricated without any metal in the magnetic field region and with no epoxy near the sensor. For protection from damage, the assembly was inserted into a 4-mm-outer-diam ceramic tube (2 mm I.D.), which did not exclude magnetic flux, even at very high field levels. Figure 1 shows a schematic diagram of a sensor.

For the first shot, three ceramic tubes were placed touching each other in a triangle. (This configuration has a radius of about 4.5 mm.) One tube had a lead flint glass sample 4.04 mm long, and the other two contained fused quartz samples 25.1 mm in length. One of the quartz samples returned no data, as the laser failed shortly before shot time, while the flint glass and the second quartz sample returned similar data, showing a peak field of about 900 T (9.0 MGauss) at the time the diagnostics were destroyed. The two working diagnostics used 632.8-nm light from HeNe lasers. The Verdet constants for this wavelength are 3.67 and 15.3 rad cm⁻¹ MGauss⁻¹ in the quartz and flint glass, respectively, and both rotations are linear to fields well above our maximum. Calibrations of the flint glass were made in Russia to an accuracy of better than 1 % and are unpublished. The fused quartz calibrations are accurate to about 2 % and were found by averaging published Verdet constant data (see Ref. 3).

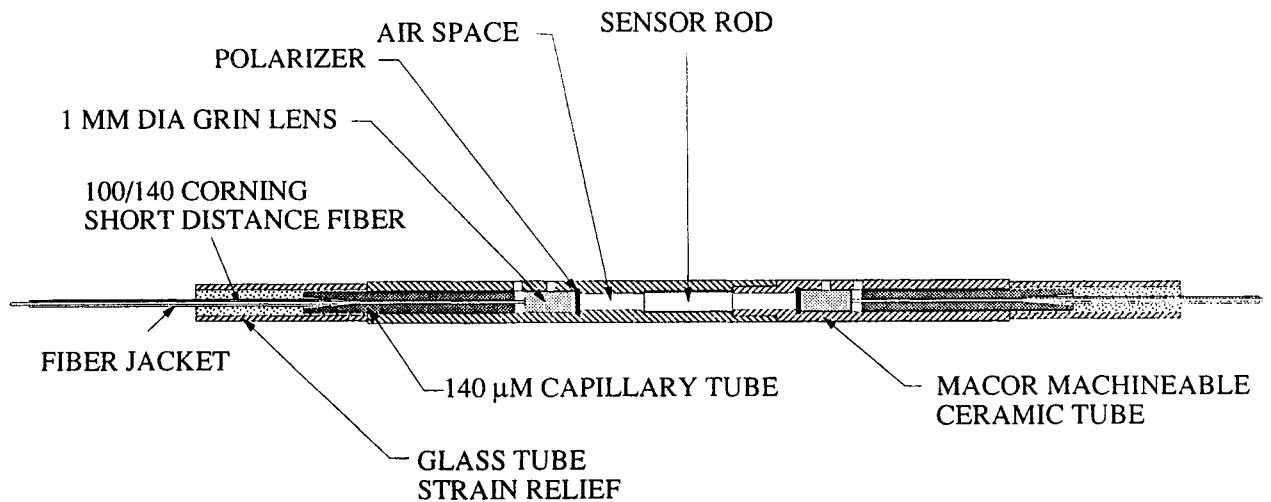


Figure 1. Schematic of a sensor assembly showing how the sensing crystal interfaces to the polarizers, lenses, fibers, and other hardware. The fibers were inserted into opaque buffers about 1 m long to protect the ends near the sensor from stray light, and then the assembly shown was inserted into a 2-mm-inner-diam ceramic tube.

Outside the tubes, in one of the three outer recesses, went an optical fiber, approximately 1 mm in diam. including its jacket, to measure the current flowing in the MC1 generator. This diagnostic, which measures the Faraday rotation of polarized light in a single-mode optical fiber run in a closed loop enclosing the current, has been described previously.³ Inductive probes to measure B-dot, the field change with time, also went near the Faraday diagnostics. A thin, opaque jacket of shrink tubing protected the fiber leads from extraneous light. The lasers and optical receivers were in a recording bunker about 20 m away.

For shots 2 through 4 we used only a single flint glass Faraday sensor for the optical field measurements, as the flint glass and quartz sensors both worked satisfactorily on shot 1. In each case, however, we also fielded the inductive sensors. On the fifth shot we replaced the flint glass with a 0.93-mm-thick CdS sample and used a HeNe laser operating at 543 nm to supply the polarized light. For this experiment we wished to determine the non-linearity in the Faraday rotation in CdS with increasing field, and to maximize the effect we used the minimum wavelength that we had readily available consistent with the light being transmitted through the sample. Here we relied on the inductive sensor for our field measurement, as we had plenty of experience from the previous shots to believe that the electrical noise levels would be sufficiently low to allow us to measure the field adequately with the inductive sensors alone and that the integrated signals would be linear with field.

Results

Figure 2 shows the magnetic field results from the first two shots. Time is measured from the moment when the MC1 generators were crowbarred, and only the final part of the flux rise is shown. The increased energy of the PBX 9501 explosive on shot 2 causes the flux to rise earlier and reach a higher final value. The current behavior was somewhat similar to that of the fields, but because the decreasing radius of the generator caused a change in the fraction of the flux leaking out the ends of the cylinder, the flux and the current are not proportional. It can be seen that the

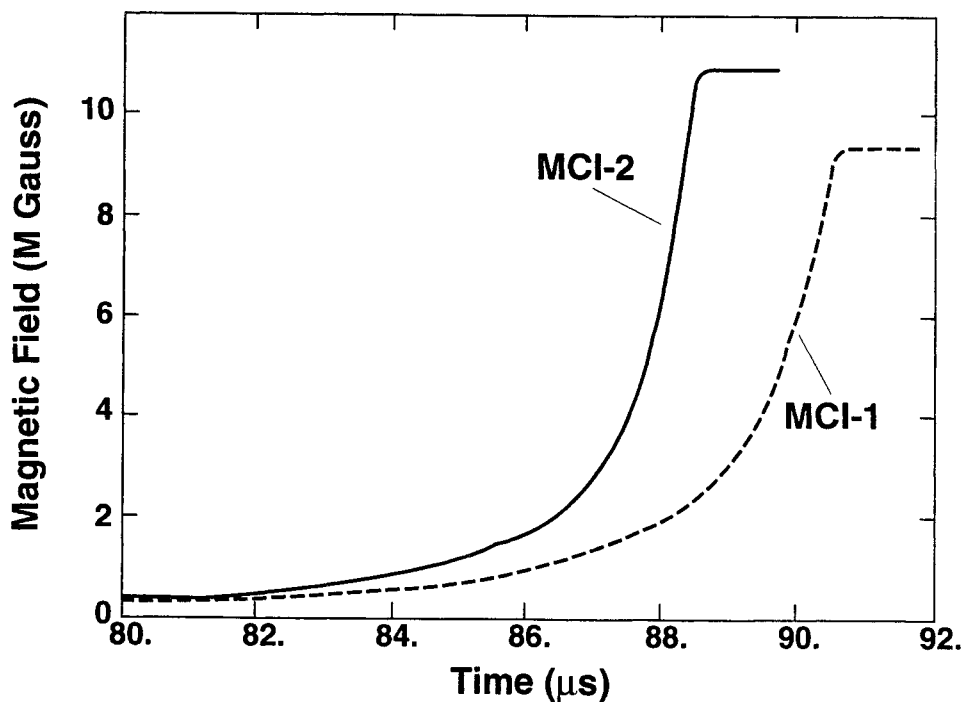


Figure 2. Faraday rotation measurements of the magnetic field from shots MC1-1 (dashed) and MC1-2 (solid). The higher explosive energy of PBX 9501 compared with Composition B is demonstrated by the faster implosion and higher final field in the second shot.

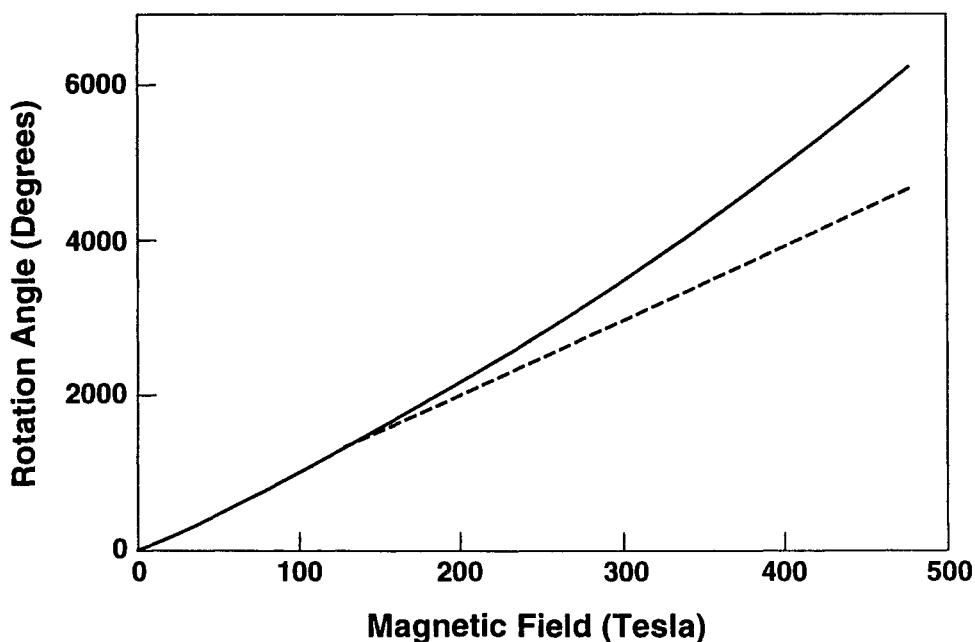


Figure 3. Faraday rotation of 543-nm light in a 0.93-mm-long CdS sample (curve) v. magnetic field for shot MC1-5. The dashed straight line is drawn to help show the deviation from linearity at high fields.

field is above half its maximum value for a time of the order of a microsecond. Because we measured a large number of fringes (approximately 20 for each probe), the uncertainty in the rotation angle is small, and the accuracies in the field measurements are determined mainly by the uncertainties in the Verdet constant calibrations.

For the last three shots the larger diagnostics packages prevented the fields from getting beyond about 500 T, at which time the implosion was halted by the generator striking the diagnostics. This turned out to be plenty of field intensity to complete the superconductivity and non-linearity experiments. The time history of the fields was similar to that seen for the first part of shot 1. The YBCO conductivity data have been published elsewhere.²

Figure 3 gives the Faraday rotation in CdS as a function of the field for 543 nm light. Above 100 T the Faraday rotation angle begins to deviate from linear, and the deviation increases with field. These data are in agreement with previous measurements⁴ of the Faraday rotation in CdS, although those results did not extend as high in field. More recent measurements and a possible explanation for the non-linearity are given in Ref. 5.

Summary

We have developed diagnostics to measure magnetic fields up to 1100 T using Faraday rotation in glass sensors small enough to survive the flux-compression implosion needed to generate the fields. The diagnostics were fit into a package with other physics experiments. The useful volume of the field was a cylinder 12 mm in diam. by several centimeters long.

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